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Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete

Proceedings
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V.M. Malhotra

Editor

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Improvements in the Properties of Concrete Utilizing "Classified Fly Ash"

by K. Ukita, S. Shigematsu, and M. Ishii

Synopsis: Fly ashes having maximum particle diameters of 20, 10 and 5 μ m, called "CLASSIFIED FLY ASH" (CFA) were investigated for their effect on concrete properties.

The CFA-concrete containing 15-30% CFA by cement weight requires less water content per unit volume. Greater strength and watertightness, lower drying shrinkage and higher resistance to alkali silica reaction are imparted to concrete by the addition of CFA. Grading or type of fly ash determines its effect on concrete.

Keywords: abrasion resistance; alkali-aggregate reactions; compressive strength; drying shrinkage; fly ash; permeability; water content

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Shun-ichi Shigematsu is Senior Research Engineer of Civil Engineering Dept., Shikoku Research Institute. He is Registered Consulting Engineer. He has been studying the effective use of coal ash especially in concrete and the durability of concrete.

Mitsuhiro Ishii is Assistant Senior Research Engineer of Civil Engineering Dept., Shikoku Research Institute. He has been studying the use of fly ash in concrete, alkali silica reaction.

INTRODUCTION

Despite increase in fly ash supply it is mostly used either as a raw material in cement production or disposed of at sites or for land reclamation. Utilization of fly ash as a concrete admixture is not very common.

The fly ash produced in recent years is of lower quality for use as a concrete admixture, because of changes in the combustion system of power plants and use of more diversified brands of coal (1).

The "classified fly ash", is produced by separating the fine components of fly ash by means of air classification. As this fly ash is made of fine particles of micron size and is of spherical shape, it was of interest to evaluate its effect in concrete.

(2) Three classes of fly ash were investigated.

EXPERIMENTAL

Materials

Fly Ash The classes of fly ash (represented by symbols) used and the methods by which they have been produced are described below.

Class

UFA: This is a product meeting JIS A (100% Standard, and is collected from electrostatic precipitator (EP) and marketed in bags (30kg units).

CFA20: Products selectivity classified and collected from rear columns (second and third columns) of EP.

CFA10: The unclassified by particle diameter.
CFA5: The unclassified by air having The typical proportions of components of and the surface particle size

Cement Normal physical properties

Fine Aggregate which was of same as was used. Its physical properties are in Table 3. In the andesite, which is in Japan, was used

Coarse Aggregate The physical properties

Mixing Water Properties and Test Properties are in Table 5.

Concrete Mixing Common concrete under the mixing conditions details are given. The properties are given in Table

Fresh Concrete Slump

The results of The slump is other words, the slump when fly ash is used as in the reference was more pronounced ash (CFA20).

Air Content The results of Fig. 4.

Although no the air content is having fine particles

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CF10: The under sieve components of UFA were classified by air classifier having a maximum particle diameter of 10 μ m.

CF5: The under sieve components of UFA obtained by air having a maximum particle diameter of 5 μ m. The typical properties as well as chemical components of these products are given in Table 1 and the surface characteristics in Fig. 1, and particle size distribution in Fig. 2.

Cement Normal portland cement was used. The physical properties of cement are given in Table 2.

Fine Aggregate The sand from crushed sandstone, which was of same origin as the coarse aggregate, was used. Its physical properties are given in Table 3. In the alkali-silica reaction test, the andesite, which is regarded as a harmful aggregate in Japan, was used.

Coarse Aggregate Crushed sandstone was used. The physical properties are given in Table 4.

Mixing Water The portable city water was used.

Properties and Test Methods

Properties tested and methods used are given in Table 5.

Concrete Mixing

Common concrete mixture proportions were used, under the mixing conditions given in Table 6. The details are given in Table 7.

The properties determined for various mixes are given in Table 7.

DISCUSSION OF RESULTS

Fresh Concrete

Slump

The results of slump test are presented in Fig. 3.

The slump is higher when fly ash is used. In other words, the amount of added water can be reduced when fly ash is used to obtain the same value of slump as in the reference concrete. This effect was more pronounced with the coarser classified fly ash (CF20).

Air Content

The results for air content are presented in Fig. 4.

Although no significant differences are observed the air content is decreased slightly when fly ash having fine particles is used.

Bleeding

The results of bleeding test are presented in Fig. 5. The data is scattered and indications are bleeding decreases as larger amounts of fine particle fly ash are used.

This tendency means that the segregation of concrete materials may be lower and the water retentivity could be enhanced. Such improvements in concrete characteristics may contribute to enhanced workability in the pumping of concreting.

Temperature Rise

The concrete containing fly ash shows a smaller temperature rise with respect to the reference concrete (Fig. 6).

The temperature rise is larger for mixes containing fly ash having finer particles. This may be due to the fine fly ash particles filling the space between cement particles (3), and accelerating the hydration of cement particles.

Hardened Concrete

Compressive Strength

The results of compressive strength test are presented in Fig. 7.

No distinctive differences between the effects of fly ashes are observed although there is a tendency for concrete containing finer fly ashes promoting the development of higher comprehensive strength. At any age concrete containing 15% fly ash yields strength equivalent to that of plain concrete.

At late ages (91 days), the strength is increased significantly for concrete with finer fly ash particles; strength equivalent to plain concrete can be obtained with fly ash content as high as 30%.

A more compacted structure and accelerated hydration of cement in the presence of fine classified fly ash particles explain most of the observations.

Water Permeability

The results of tests conducted on concrete cured for 28 or 91 days are presented in Fig. 8.

For the samples cured for 28 days, the water permeability was lower for concrete with finer particles and containing 15% fly ash. Sample having a fly ash content of 30%, shows higher permeability than that of the reference concrete. The pozzolanic action may be responsible for the different permeability values.

It can be concluded that the water-tightness of concrete can be increased when classified fly ash is used in place of un-classified fly ash. Water-tightness value depends on proportion and particle size of fly ash.

Abrasion Resistance

The resistance of samples cured for 28 days is presented in Fig. 9.

At the fly ash content of 15%, the resistance increases. The abrasion resistance of concrete containing finer fly ash is higher than that of reference concrete. At a fly ash content of 30%, the resistance was reduced. At a fly ash content of 45%, the resistance is lower than that of reference concrete. At a fly ash content of 60%, the resistance increases.

Drying Shrinkage

The results of drying shrinkage test are presented in Fig. 10.

At a fly ash content of 15%, the shrinkage tends to be smaller than that of plain concrete. At a fly ash content of 30%, the shrinkage is larger than that of plain concrete. Samples with fly ash content of 45% and 60% show shrinkage values similar to that of plain concrete.

Shrinkage values of fly ash concrete are similar to those of plain concrete at a constant water-cement ratio.

Relation between Compressive Strength and Permeability

Relation between Compressive Strength and Permeability

The relation between compressive strength and permeated depth is shown in Fig. 11.

It can be seen that the permeability of concrete increases with the increase of concrete strength. The water permeability value decreases with the increase of concrete age.

Relation between Compressive Strength and Abrasion Resistance

The relation between compressive strength and abrasion resistance is shown in Fig. 12.

It can be seen that the abrasion resistance of concrete has a relatively strong correlation with compressive strength. The value of abrasion resistance increases with the increase of concrete strength.

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Abrasion Resistance

The resistance to abrasion conducted on concrete samples cured for 28 days or 91 days is given in Fig. 9.

At the fly ash proportion of 15%, the abrasion resistance increases with the fineness of fly ash. The abrasion resistance of the sample with CFA5 fly ash containing finest particles is higher than the reference concrete. In other cases, the abrasion resistance was reduced by several percent to 20%. At a fly ash content of 30%, the abrasion resistance is lower than that of the reference, although the resistance increases with fineness of fly ash.

Drying Shrinkage

The results for 91 days samples are given in Fig. 10.

At a fly ash content of 15%, the amount of drying shrinkage tends to be lower with samples containing finer fly ash. The shrinkage is equal or lower than that of the plain concrete.

Samples with fly ash content of 30%, show higher shrinkage.

Shrinkage values would have been lower in all fly ash concrete samples if they had been lower in all fly ash concrete samples if they had been made at a constant workability instead of at a constant water-cement ratio.

Relation between Compressive Strength and Other Properties

Relation between Compressive Strength and Water Permeability

The relation between comprehensive strength and permeated depth is illustrated in Fig. 11.

It can be seen in the figure that watertightness of concrete increases as the compressive strength increases. The water-tightness enhances with the age of concrete.

Relation between Compressive Strength and Abrasion Resistance

The relation between the abrasion values and compressive strength is illustrated in Fig. 12.

It can be seen in the figure that the abrasion resistance of concrete containing classified fly ash has a relatively strong correlation with compressive strength, the values decreasing with the increases in strength.

Relation between Compressive Strength and Drying Shrinkage

The relation between the shrinkage of 91 days concrete and the compressive strength (at 7 days) is illustrated in Fig. 13.

It can be seen in the figure that there is no correlation between drying shrinkage and compressive strength. The drying shrinkage seems to correlate better with the aggregate volume in concrete (4).

Effect of Particle Size on Compressive Strength

It is difficult to quantify the particle sizes of solid components in concrete, as they change with time of hydration and pozzolanic reaction. For this reason, the particle size of all solid components just before mixing (arbitrarily called the initial composite particle size) was taken into consideration.

The relationship between the equivalent specific surface area (calculated from the initial composite particle size distribution) and compressive strength is illustrated in Fig. 14. The calculations are described below:

Equivalent specific surface area denoted by A_s (cm²/g) can be obtained from the following equation:

$$A_s = [(6/\pi) \cdot \sum (X_i/d_i)], 100$$

where, \sum represents the summation from lower to upper limit with respect to the 'i'-th particle size.

ρ is the equivalent specific weight of composite material, which can be expressed by the following equation:

$$\rho = [C + F + S + G] / [C/\rho_c + F/\rho_f + S/\rho_s + G/\rho_g]$$

C, ρ_c : Cement content and specific weight

S, ρ_s : Fine aggregate content and specific weight (dry surface)

G, ρ_g : Coarse aggregate content and specific weight (dry basis)

F, ρ_f : Fly ash content and specific weight

X_i : Percentage of materials with particle size between d_i and d_{i+1}

d_i : Particle size of 'i'-th class

Following conclusions can be drawn:

Higher compressive strength is obtained with larger equivalent specific surface area.

When the fly ash is in long term concrete compared with short term concrete, that this tendency is size, but also by the classified fly ash. It is important to consider the concrete material ratio (or the amount of fly ash).

Effects of Alkali-Silica Reaction

Mortar tests (ASTM C189 test results) are known to be a typical example of the alkali-silica reaction. The alkali content of the mortar was fixed at an amount of 1.0%.

Results of Fig. 16 show that the alkali-silica reaction is effective. Finer fly ash is more effective. Larger fly ash is less effective. This reaction may be accelerated by the alkali content.

The expansion of concrete significantly increases with the volume of non-classified fly ash. The expansion is reduced by the use of classified fly ash. The expansion is increased by fly ash at 91 days. Using 15% fly ash, the expansion is increased. Abrasion of concrete is lower than the value of non-classified fly ash. At earlier ages the value are equal or lower. The expansion can be controlled by the strength. The par in addition to the influences the strength of the concrete. The action of classification is more pronounced.

In conclusion, the improvement effect of concrete, such as the enhancement of strength and suppression of alkali-silica reaction, is more pronounced by the use of classified fly ash.

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When the fly ash content is 15%, the increase in long term concrete strength is pronounced as compared with short-term strength. It can be assumed that this tendency is caused not only by the particle size, but also by the pozzolanic reaction of classified fly ash. In these calculations it is important to consider the particle size distribution of concrete materials as well as the water: cement ratio (or the amount of hydrating materials).

Effects on Alkali-Silica Reaction

Mortar tests were conducted by using andesite (ASTM C1259 test results given in Fig. 15) that is known to be a typical harmful aggregate in Japan. The alkali content of cement (R_2O) was 1.2% and fly ash was mixed at an amount of 15% (30% in one test). Results of Fig. 16 indicate the following:

Alkali silica reaction is greatly suppressed by fly ash. Finer particle size is even more effective. Larger amounts of fly ash also inhibit this reaction. It should be recognized that the reaction may be accelerated by 'pessimum amount', depending on the kind and proportion of fly ash (5).

CONCLUSION

Incorporation of fly ash affects the properties of concrete significantly. The water content per unit volume of normal concrete is reduced when classified fly ash is used. Air content is not affected but concrete becomes more compacted. Bleeding is reduced and the rate of reaction is increased by fly ash. The compressive strength is increased at 91 days with finer particles of fly ash. Using 15% fly ash water tightness can be increased. Abrasion resistance is increased with finer particle size at a fly ash content of 15%. At earlier ages the shrinkage of fly ash concrete is lower than the reference but at later ages the values are equal or higher. All properties, except shrinkage, can be correlated with the compressive strength. The particle size of solids in concrete, in addition to the water-cement or water-binder ratio, influences the strength of concrete. The inhibitive action of classified fly ash on alkali silica reaction is more pronounced than the unclassified fly ash.

In conclusion, we have identified the quality improvement effects of classified fly ash mixed in concrete, such as reduction of unit water content, enhancement of strength and water-tightness, and suppression of alkali silica reaction.

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TABLE 1--PHYSICAL PROPERTIES AND CHEMICAL COMPOSITIONS OF FLY ASH

Type of Fly Ash	Physical Properties			Chemical Compositions (%) •							
	Specific Gravity	Surface Area, m ² /g	Mean Particle Size, μ m	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃

TABLE 1--PHYSICAL PROPERTIES AND CHEMICAL COMPOSITIONS OF FLY ASH

Type of Fly Ash	Physical Properties			Chemical Compositions (%)								
	Specific Gravity	Surface Area, Blaine (cm ² /g)	Mean Particle Size (µm)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	lg. loss
UFA	2.28	3550	17.6	54.6	28.3	6.55	3.97	1.36	1.08	0.92	0.59	2.78
CF A20	2.31	5500	7.5	52.5	30.5	5.77	2.75	1.05	1.07	0.89	0.71	4.37
CF A10	2.46	8450	3.3	53.4	31.6	4.08	2.21	1.01	1.13	0.95	0.84	4.51
CF A5	2.51	12400	2.2	53.8	29.5	4.52	2.03	0.93	0.99	0.81	1.24	5.54

• Analysis Method: JIS M 8815

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TABLE 2--PHYSICAL PROPERTIES OF CEMENT

Type	Specific Gravity	Surface Area (cm ² /g)
Normal portland	3.16	31.50

TABLE 3--PHYSICAL PROPERTIES OF FINE AGGREGATE

T y p e	Maximum size (mm)	Specific Gravity	Water absorption (%)	Grading Distribution mm (retained %)					Fineness modulus	
				5	2.5	1.2	0.6	0.3		0.15
Crushed Sand	5	2.58	1.31	0	0	28	49	70	90	2.46

TABLE 4--PHYSICAL PROPERTIES OF COARSE AGGREGATE

Type	Maximum size (mm)	Specific Gravity	Water absorption (%)	Grading Distribution mm (retained %)				Fineness modulus
				20	10	5	2.5	
Crushed Stone	20	2.60	1.24	2	57	96	99	6.54

TABLE 5--PROPERTIES AND TEST METHODS

Properties	Test Methods		Note
	Slump	Air	
Fresh	JIS A 1101	JIS A 1128	

TABLE 5--PROPERTIES AND TEST METHODS

Properties	Test Methods	Note
Slump	JIS A 1101	
Air	JIS A 1128	
Bleeding	JIS A 1123	
Rise in Temperature	Simple method	
Comp. Strength	JIS A 1108	
Abrasion Resistance	Simple method	
Water Permeability	Input method	Permeated Depth
Drying Shrinkage	JIS A 1129	
Alkali-Silica Reactivity	JIS A 5308	

TABLE 6--MIX CONDITION FOR CONCRETE

Water-Binder ratio (W/B) (%)	Sand-Aggregate ratio (s/a) (%)	Unit Weight (kg/m ³)		Note
		Binder* (B)	Water (W)	
0.55	0.45	340	187	* Binder (B) = Cement (C) + Fly Ash (F) (Concrete) Non-AI Concrete

Crushed Stone	2.60	1.24	2	57	96	99	6.54
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TABLE 7--CONCRETE MIXTURE PROPORTIONS

No.	Size Type	Type of F.A.	F (C/F)	Gmax. (mm)	w/c (C/F)	s/a (%)	Water (L)	Cement (C)	Fly Ash (FA)	F. Acrete. (S)	C. Acrete. (C)
1	Plain	-	30	20	55	15	187	310	0	738	923
2	UFA15	UFA15	15	20	55	45	187	289	51	743	913
3	UFA30	UFA30	30	20	55	15	187	238	102	733	905
4	CFA2015	CFA2015	15	20	55	15	187	289	51	743	913
5	CFA2030	CFA2030	30	20	55	45	187	238	102	735	905
6	CFA1015	CFA1015	15	20	55	45	187	289	51	743	915
7	CFA1030	CFA1030	30	20	55	45	187	238	102	738	910
8	CFA515	CFA515	15	20	55	45	187	289	51	743	918
9	CFA530	CFA530	30	20	55	45	187	238	102	738	905

TABLE 8--PROPERTIES DETERMINED

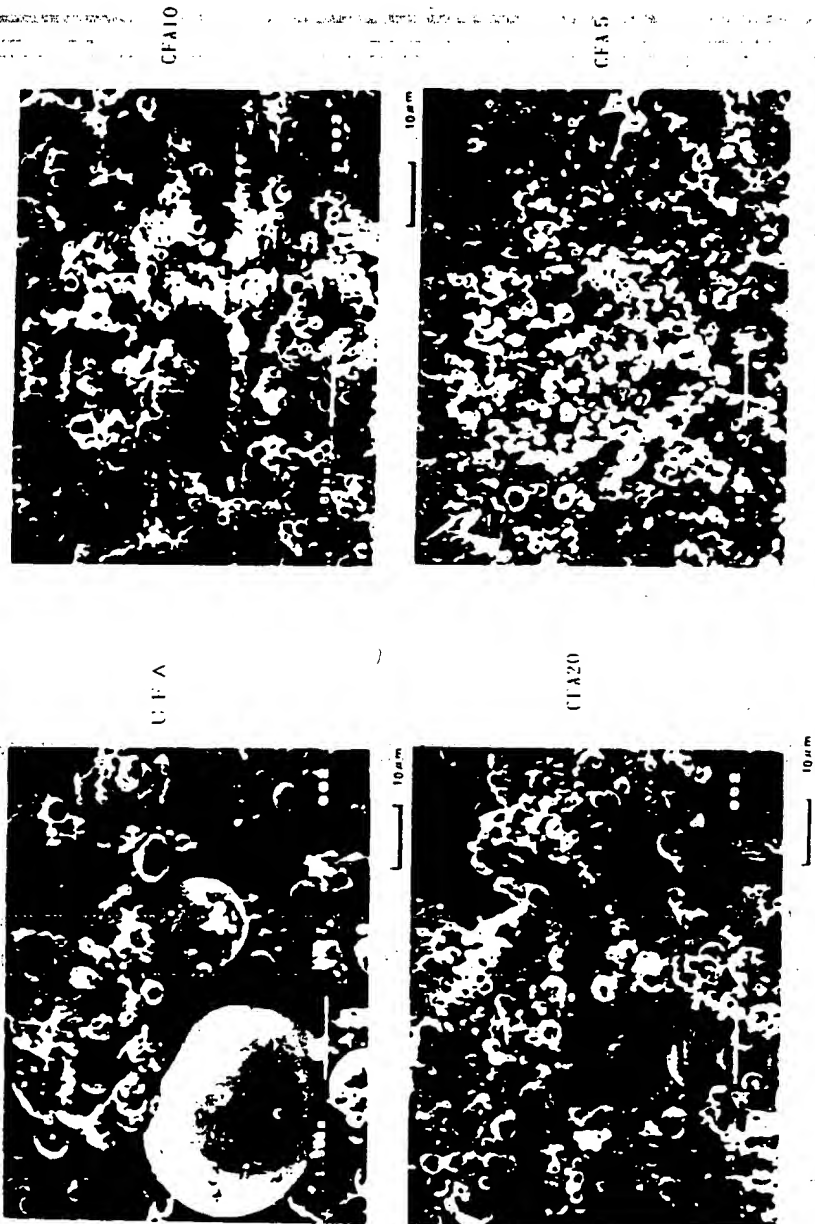


Fig. 1--Surface characteristics of fly ashes

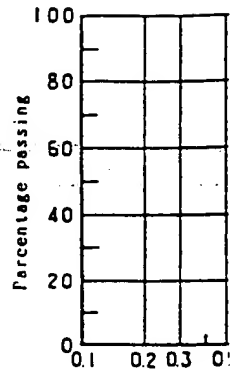


Fig. 2--Part

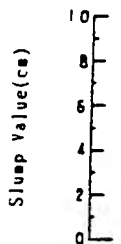


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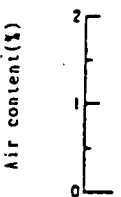


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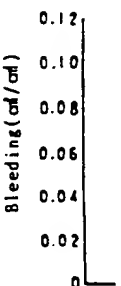


Fig. 5

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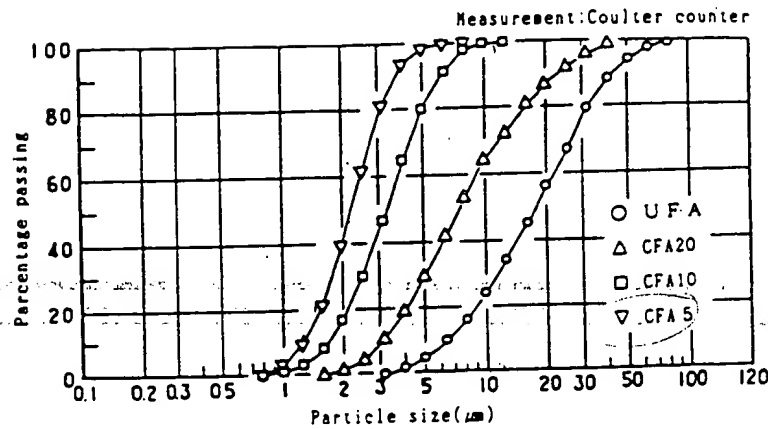


Fig. 2--Particle size distribution of fly ashes

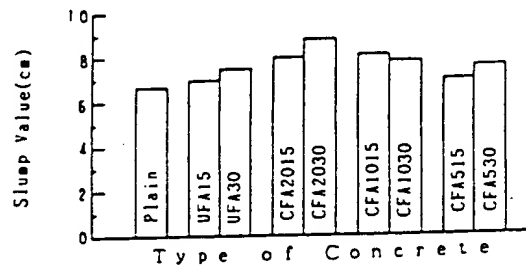


Fig. 3--Results of slump test

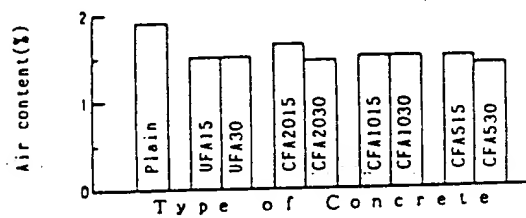


Fig. 4--Results of air test

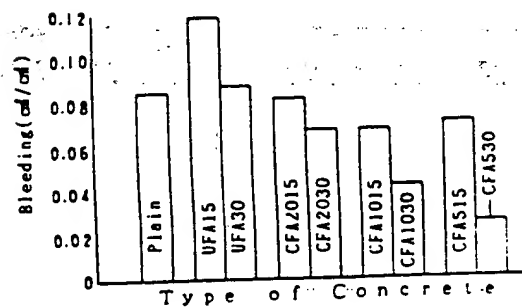


Fig. 5--Results of bleeding test

Fig. 1--Surface characteristics of fly ashes

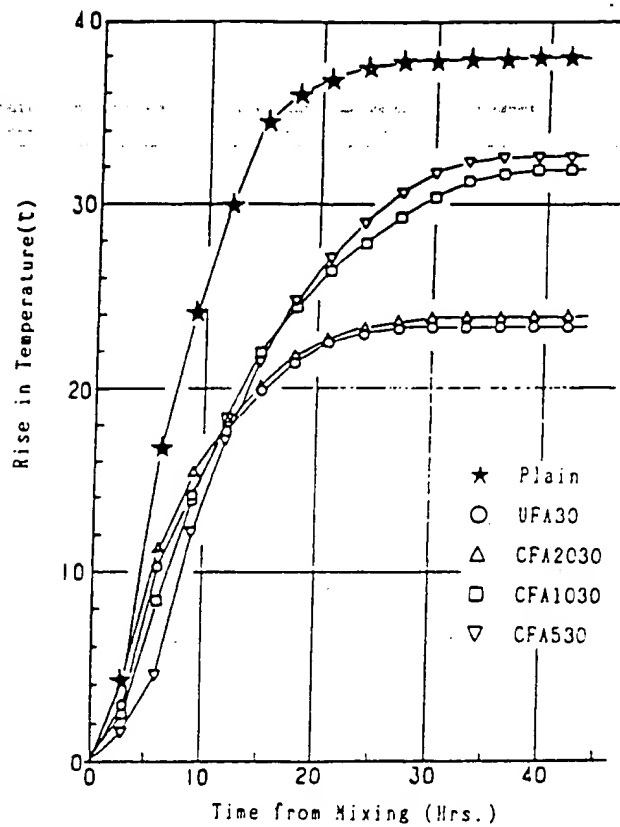


Fig. 6--Results of rise in temperature

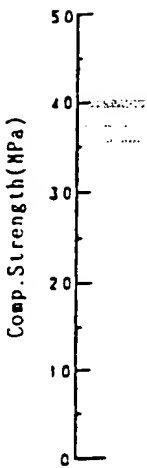


Fig. 7--

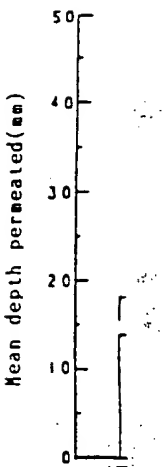


Fig. 8--

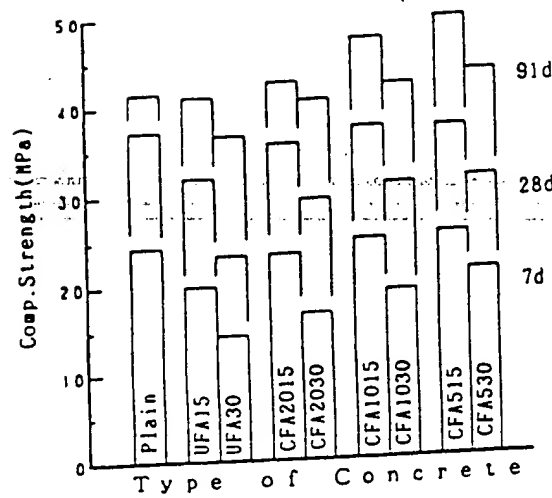


Fig. 7--Results of compressive strength

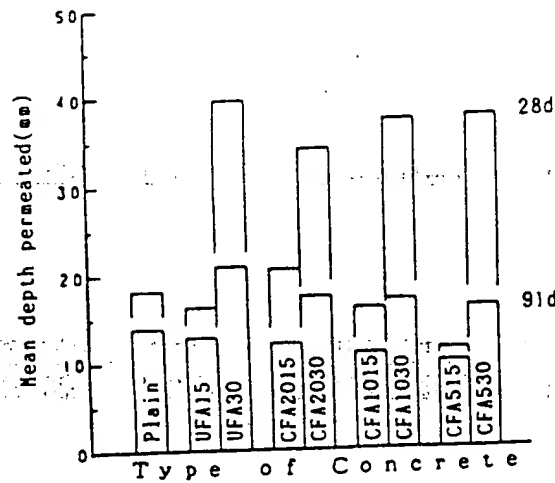


Fig. 8--Results of water permeability

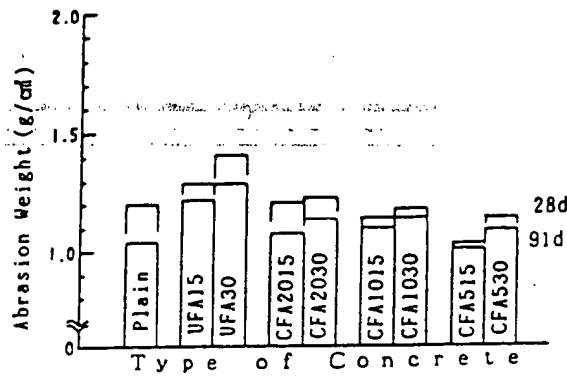


Fig. 9--Results of abrasion

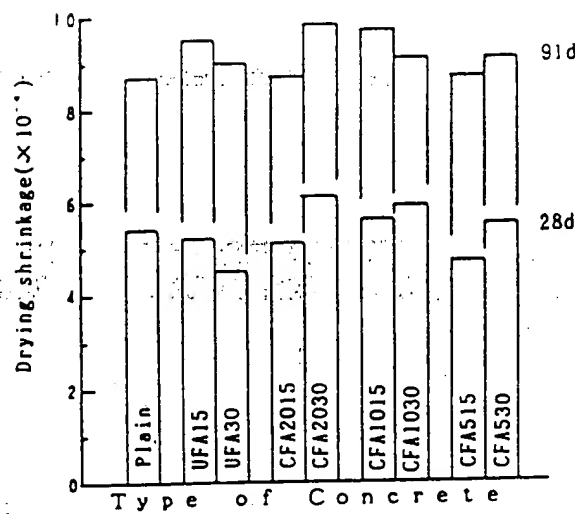


Fig. 10--Results of drying shrinkage



Fig. 11
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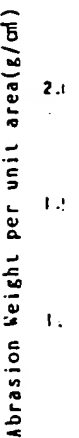


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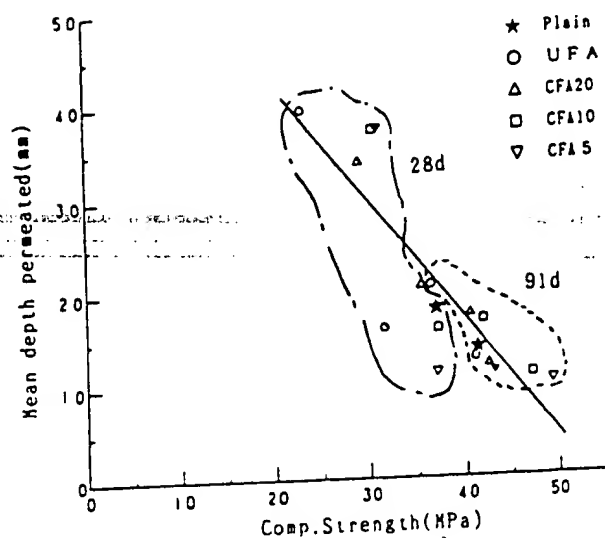


Fig. 11--Relation between mean depth permeated and compressive strength

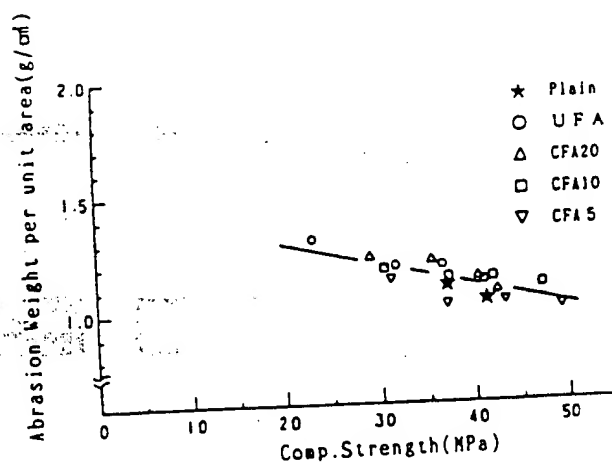


Fig. 12--Relation between abrasion weight per unit area and compressive strength

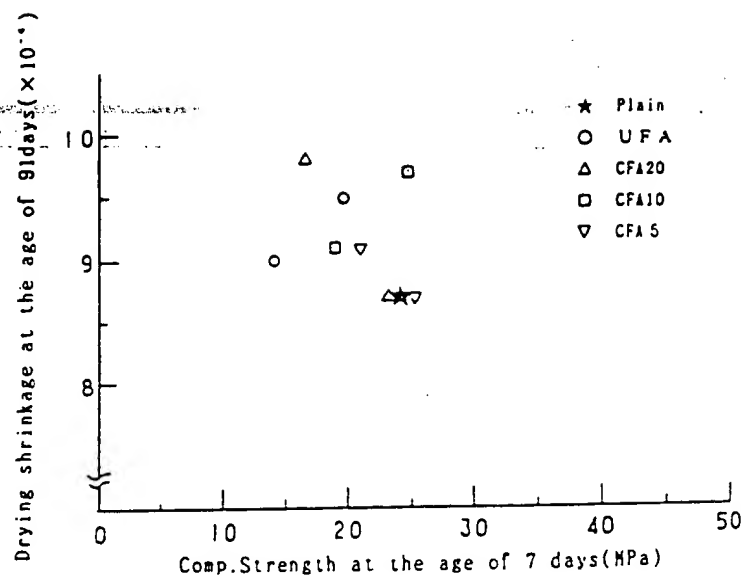
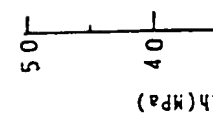
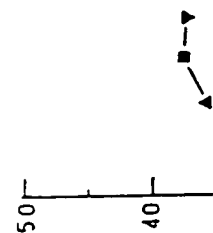
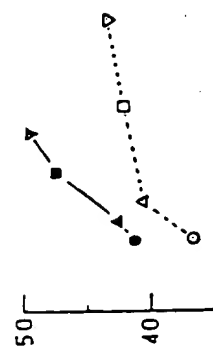


Fig. 13--Relation between drying shrinkage and compressive strength



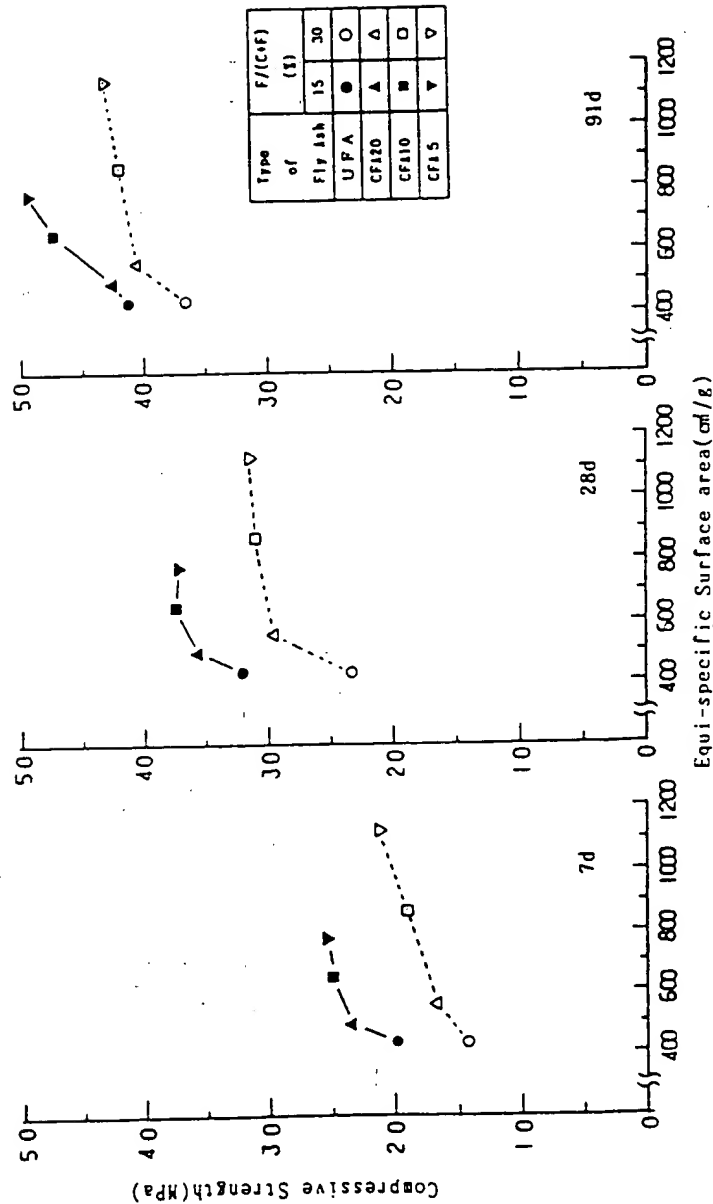


Fig. 14--Relationship between compressive strength and equi-specific surface area of all solid material in concrete

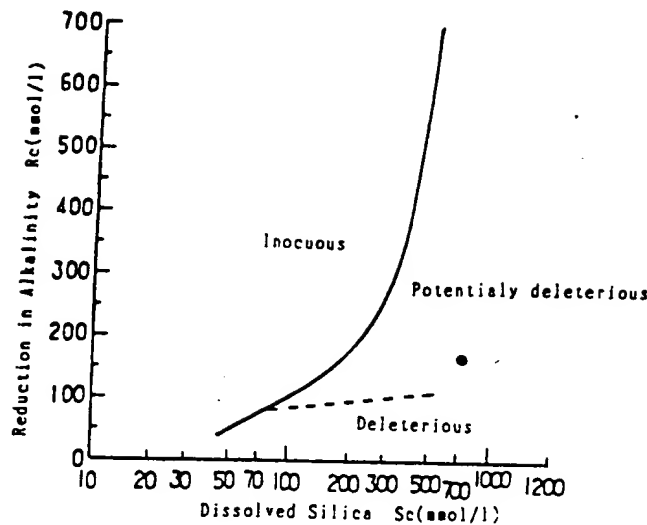


Fig. 15--Alkali silica reactivity of aggregate used (according to ASTM C289)

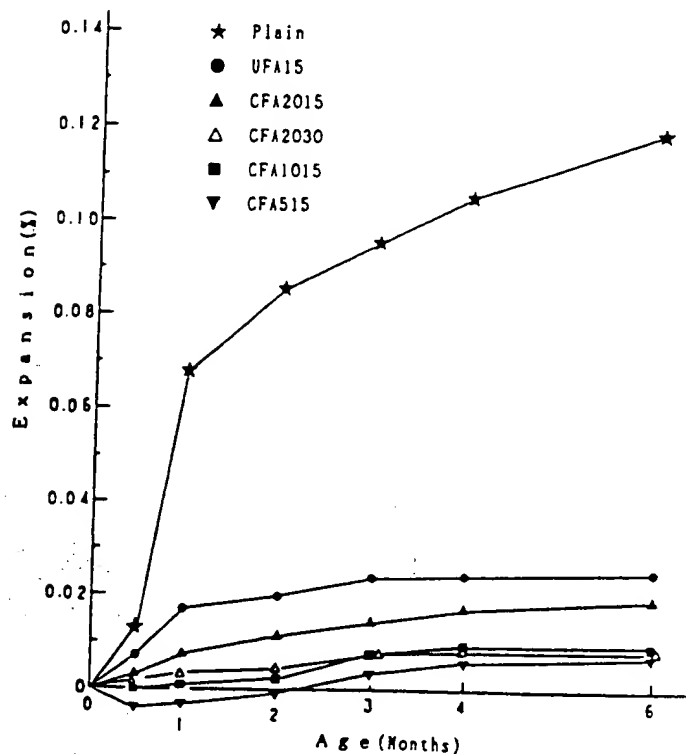


Fig. 16--Results of alkali silica reactivity test for mortar

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Synopsis: A study of fly ash from Lingar, a high-efficiency air-cleaning grade with nominal $-45\ \mu\text{m}$ fraction from improve the quality of spherical particles of spherical particles.

The raw fly ash with the requirement improved pozzolanic alkali-aggregate reaction the $-45\ \mu\text{m}$ fraction strength at 28d. This beneficiation of the improved strength de-

The hydration of at $w/c=0.5$ and curing substitution increased major ions in pore solution control. Mechanism: curing age are discussed general, the ash-containing

At 28d there was expected due to pozzolanic reactivity of increased C-S-H products. At 28d, the chemical reactivity of nucleation sites for C-S curing ages extended to in these systems.

The pore structure porosimetry and their uniquely related to the pastes serve to close intrusion. Whether this (possibly as a result of) remains to be established

Keywords: alkali ash; hydration; micro permeability; porosity